URAT: astrometric requirements and design history

Norbert Zacharias[a], Uwe Laux[b], Andrew Rakich[c], and Harland Epps[d]

[a]U.S. Naval Observatory, 3450 Mass. Ave. NW, Washington DC 20392
[b]Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany
[c]EOS Space Systems, 111 Canberra Ave, Griffith, ACT 2603, Australia
[d]UC, Santa Cruz, Lick Observatory, Nat.Sc.2, Rm 191, Santa Cruz, CA 95064

ABSTRACT

The U.S. Naval Observatory Robotic Astrometric Telescope (URAT) project aims at a highly accurate (5 mas), ground-based, all-sky survey. Requirements are presented for the optics and telescope for this 0.85 m aperture, 4.5 degree diameter field-of-view, specialized instrument, which are close to the capability of the industry. The history of the design process is presented as well as astrometric performance evaluations of the toleranced, optical design, with expected wavefront errors included.

Keywords: optics design, astrometry, wide-field, sky-survey, URAT, USNO

1. INTRODUCTION

From 1998 to 2004 the U.S. Naval Observatory (USNO) conducted an astrometric, all-sky survey to 16th magnitude with its 20 cm aperture Twin Astrograph, resulting in the USNO CCD Astrograph Catalog (UCAC), with its second release (UCAC2) made public in 2003.[1] Around the year 2000 the USNO began preparations for a follow-up project, the USNO Robotic Astrometric Telescope (URAT), a dedicated, astrometric, 1-meter size telescope with a wide field of view for an all-sky survey going much deeper than UCAC and on a positional accuracy level aiming at 5 milliarcsecond (mas) standard error per coordinate.

The idea of such a telescope goes back to the late 1980s,[2] then envisioned for photographic plates. The purpose of such a telescope is threefold. First URAT aims at the densification of the celestial reference frame, providing a large number of accurate reference stars[3] to support, for example, general, deep sky surveys like PanSTARRs and LSST, and to support astrometry in our solar system, as outlined in the recent decadal survey.[4] Second, URAT provides absolute proper motions on an inertial system, enabling significant galactic dynamics studies in the pre-Gaia era. Third, URAT will be able to observe trigonometric parallaxes of many thousands of stars unbiased by selection effects like high proper motion targets. More details about the URAT project in general can be found elsewhere.[5,6]

2. REQUIREMENTS

2.1. General

The basic parameters and requirements of the proposed new telescope are summarized in Table 1.

The goal is to reach about magnitude 21 in a few minutes exposure time and cover an entire hemisphere about 6 times per year in a relatively narrow astrometric passband. In order to cover a large amount of sky, critical sampling near 2 pixel per full width at half maximum (FWHM) is required. The limiting magnitude requirement leads to a 1-meter class aperture. In order to ease the f/ratio requirement, a small pixel size (about 9 μm) was adopted. These basic project parameters then determine the focal length and field-of-view requirements.

Further author information: (Send correspondence to N.Z.)
N.Z.: E-mail: nz@usno.navy.mil, telephone: 1 202 762 1423
U.L.: E-mail: laux@tls-tautenburg.de
A.R.: E-mail: arakich@eos-aus.com
H.E.: E-mail: epps@skewray.ucolick.org

Table 1. Basic data of URAT.

aperture	0.85	m	
effective aperture	0.60	m	equivalent unobstr. area
focal length	3.60	m	
image scale	57.3	"/mm	= 57.3 mas/μm
field of view	4.00	deg	diameter design goal
	4.50	deg	usable (vignetted)
passband	$650 - 800$	nm	astrometric
	$500 - 950$	nm	photometric
stray light, ghost images	10 magnitudes fainter than direct light / surface area		
focusing	by moving the backend of the telescope		
telescope flip:	2 telescope orientations, 180° w.r.t. sky		
mount	equatorial		
guiding	active, with 2 guide detectors in focal plane		
operation	robotic		
detector	4 CCDs, each 10.6k $\times$ 10.6k pixel		

The passband needs to be in the V to I range (peak detector quantum efficiencies, large flux of "normal" stars). Exclusion of the H_α line is important to avoid complications with galactic nebulae; the emphasis is on stars. The UCAC project chose a bandbass just blue of H_α, while for URAT a passband just red of H_α has been adopted. This will mitigate the differential refraction effects, both from the Earth's atmosphere and from refractive optics design considerations. The width of the passband is chosen as a compromise between reaching a deep limiting magnitude and minimizing differential color effects. The optics design goal was set to cover 650 to 800 nm, while the passband to be used will likely be about 670 to 770 nm.

Table 2. Specific astrometric requirements for URAT.

general:	
good image quality	$\geq$ 70 % Strehl ratio
entrance pupil	circular symmetric, no spider structure
flat field	no significant field curvature
stability	variations of "high order terms"
	on $\leq$ 100 nm level (thermal, flexure)
distortion:	
geom. optical distortion	$\leq$ 1 arcsec / degree^3
deviation from 3rd order dist.	$\leq$ 300 nm over 4° diameter field
lateral color:	
center-of-mass centroids	within 400 nm over astrom. band
peak location centroids	within 400 nm over astrom. band
symmetric images:	
all PSFs + 0.7" seeing	centroids 90% and 1% within 400 nm

The “flip” of the telescope is a required to perform astrometric calibration observations. The same area of the sky will be observed with the entire telescope tube assembly plus camera in 2 possible orientations which are rotated by 180° around the optical axis with respect to each other. At the astrograph we achieved this by observing with the telescope from the East and West side of the pier (B&C equatorial mount). An equatorial fork mount would be an option for URAT if it can be rotated by a sufficiently large angle and if the telescope can swing through the “fork” to both sides.

A requirement which entered the process at a late stage was the ability of URAT to also perform photometric surveys in at least 2 colors within the V to I range of the spectrum. Color information is required for many applications to predict the brightness of stars in non-standard passbands often used in DoD instrumentation. No strict astrometric performance is required for the 500 to 900 nm band; a general “good” image quality, like “nearly diffraction limited” for the expected medium seeing of 1 arcsec FWHM is sufficient for photometric surveys, with re-focusing of the instrument between filters allowed. The detector development is in progress[7] with a funded phase II Small Business Innovation in Research (SBIR) program. A complete prototype camera including a single 10.6k by 10.6k thinned CCD is expected to be delivered to USNO by the end of 2006.[8]

2.2. Astrometric Requirements

The requirements specifically relevant for astometry are summarized in Table 2. The general image quality, which is typically defined by a Strehl ratio is often the most important requirement for telescope designs, demanding a nearly diffraction limited design over a specified field of view and passband. For URAT this is of minor importance and generally “sharp” images follow from the other, more specific requirements for astrometric mapping.

Particularly problematic is the requirement of a circular symmetric entrance pupil without secondary mirror spider structures which prohibited the use of most traditional optical designs. The reason for this requirement is to be able to measure very bright and very faint stars simultaneously. It is assumed that the detector for URAT does not “bleed” charge when saturation is reached. Accurate positions could then be obtained even from overexposed stellar images by just rejecting the central, saturated pixels of the image profile. Conventional designs with diffraction spikes from secondary mirror support structures would prevent this. Curved spiders were suggested[9,10] which reduce the effect of “spikes”, but a rigorous approach was adopted here particularly for DoD applications.

At first it seems that a general pattern of geometric optical distortion, even if very large, could be tolerated for an astrometric telescope as long as the stability is guaranteed. However, extensive calibrations would be required to achieve satisfactory astrometric results from such a telescope, which is rendered impossible in practice when considering the limited number of reference stars available with typically unknown colors or considering the number of “bins” needed to map out the focal plane geometric distortions to within a specified, tight tolerance and bridge gradients between bins. Thus a relatively small optical distortion is required to begin with, which then will need to be calibrated to the measure accuracy level with as few parameters as possible. That is why only a 3rd order term is allowed here with higher order deviations smaller than 300 nm in the focal plane, which corresponds to 17 mas in extreme cases (usually at the edge of the field), with much better performance on average.

Because of the generally unknown spectral energy distribution of the stars to be observed, the images of stars must have “the same” centroid regardless of wavelength, which leads to a strict lateral color requirement. For all field points within the 4° diameter field of view and for all wavelengths in the astrometric passband (650–800 nm) the maximal difference in image centroids of any 2 monochromatic point spread functions (PSF) shall not exceed 400 nm for a 90% confidence level of the “as-built” system.* When dealing with such tight tolerances the “centroid” needs to be defined more precisely. Due to possible small image profile asymmetries (coma aberrations) there are different definitions of “centroid”. Here the lateral color requirement needs to be obeyed by 2 definitions: center-of-mass centroid of a PSF (taking the entire flux) and the peak location of the PSF, as defined by the center-of-mass position of the 90% and above contour level of the PSF, after folding with a 2-dimensional Gaussian seeing profile of 0.7 arcsec FWHM. The first lateral color criterion could be checked by ZEMAX directly, while the latter required a dedicated astrometric evaluation (see below).

*The wording “as-built” used in quotes is used in this paper for an optical system which includes expected wave-front errors from manufacturing and alignment errors as derived from simulations of the toleranced system.

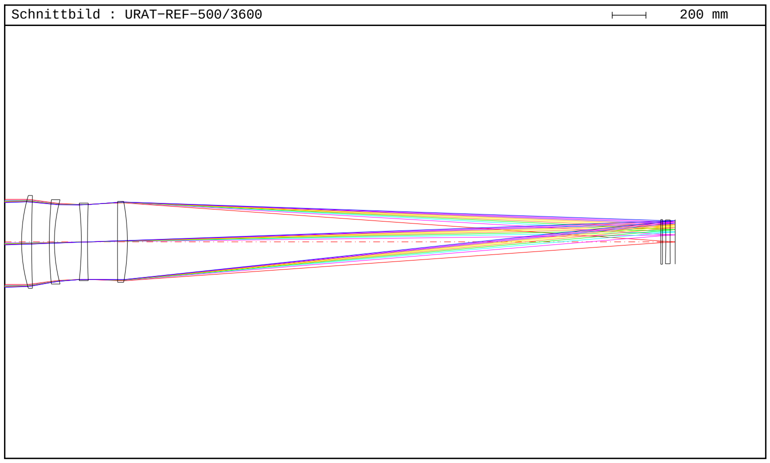

Figure 1. Optics layout of pure refractive solution.

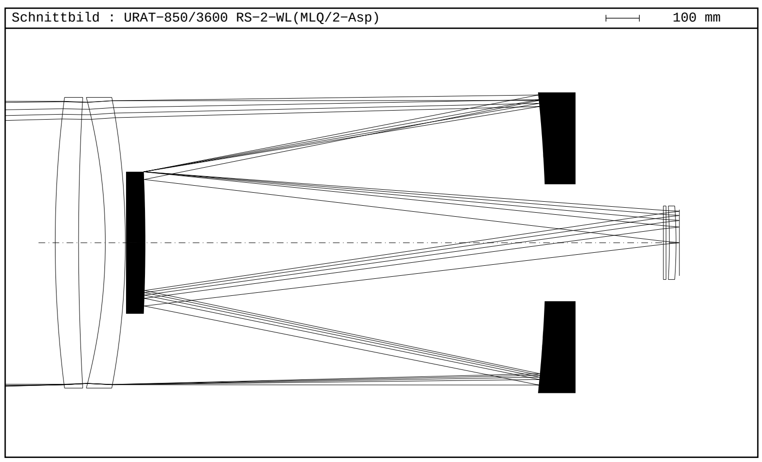

Figure 2. Optics layout of RS2b design.

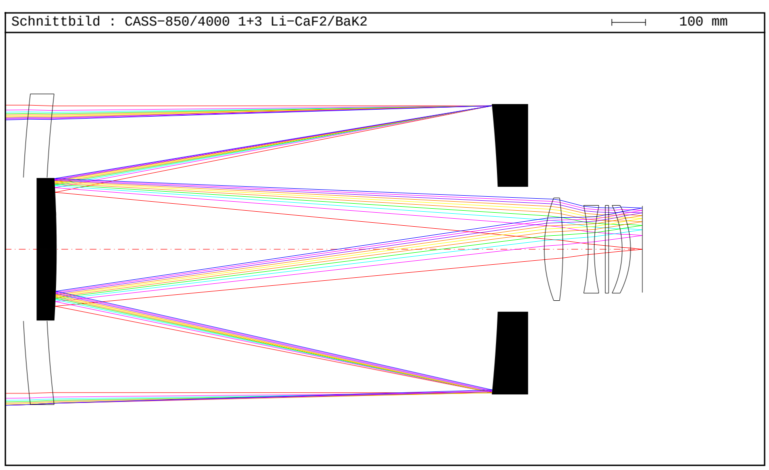

Figure 3. Optics layout of 1CaF design.

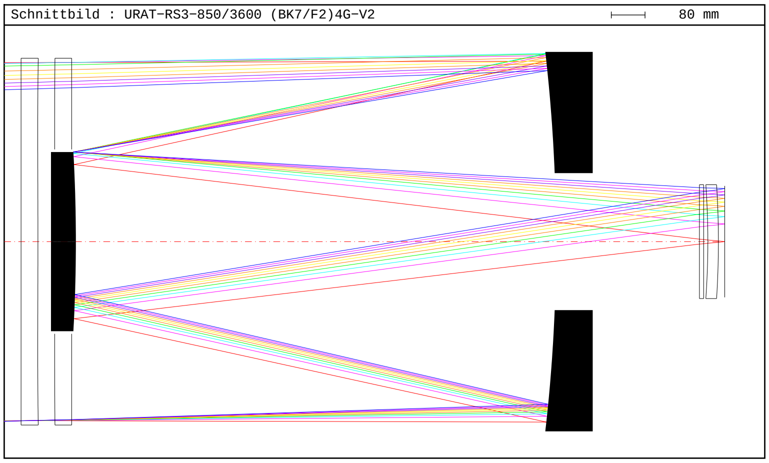

Figure 4. Optics layout of RS3 design.

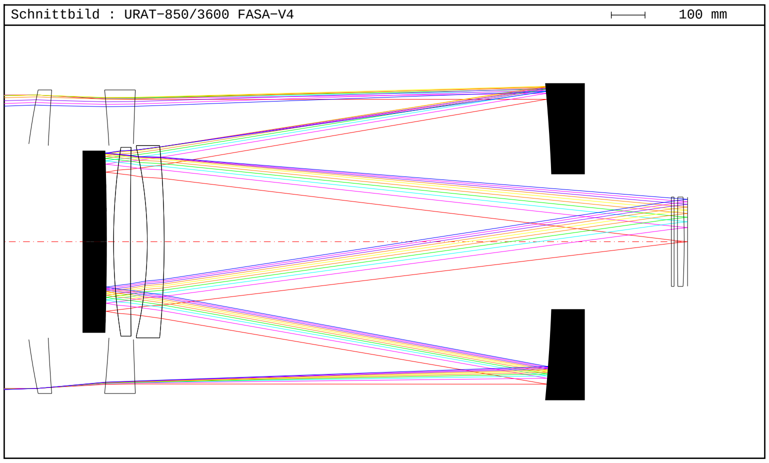

Figure 5. Optics layout of FASA2 v4 design.

Similarly, the image asymmetry is bound to give a difference in centroid positions nowhere exceeding 400 nm for the "as-built" system and folded with 0.7 arcsec seeing when comparing the 90% and 1% flux level of any PSF in the astrometric field-of-view and passband. At 0.7 arcsec seeing the PSFs will be undersampled with about 1.5 pixels per FWHM and "pixel-phase" centroid bias effects will be taken into consideration similarly to the UCAC reduction procedures.[1]

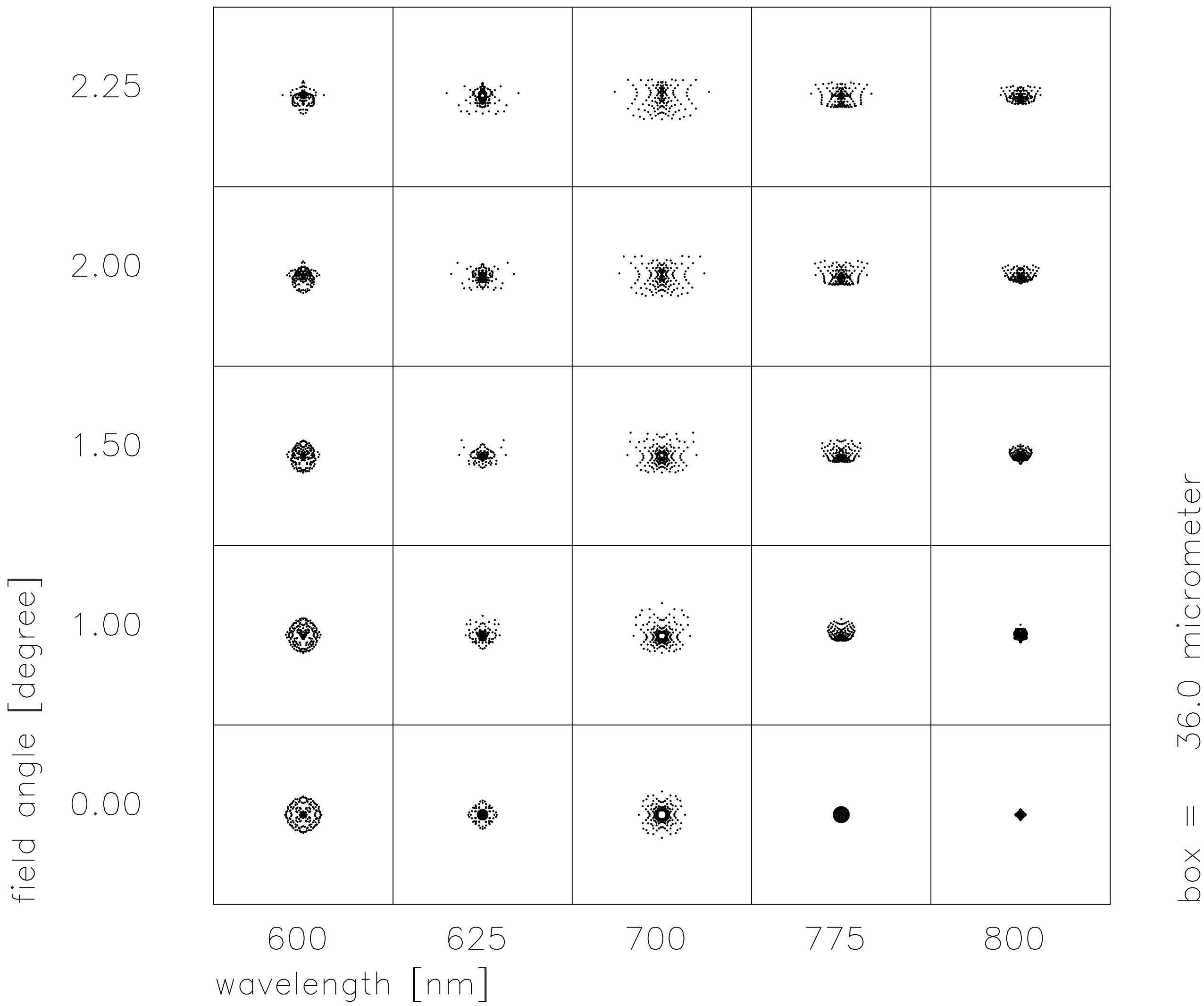

Figure 6. Spot diagrams of RS3 design.

3. DESIGN OPTIONS

Design work specifically for URAT began around the year 2001. Modified Richter-Slevogt systems were proposed by one of us (U.L.), which were presented e.g. at the Lowell astrometry meeting[11] followed by a single full-aperture lens approach from EOST (A.R.). Initial contacts with various vendors seemed to indicate that a 1-meter-class telescope even with "corrector plates" is not a problem. However, after having presented details (highly aspheric RS3 system for example) and the required tolerances, we quickly reached the state-of-the-art engineering limits with high price tags.

The 5 designs investigated are summarized in Table 3 with optical layout diagrams shown in Figures 1 to 5.

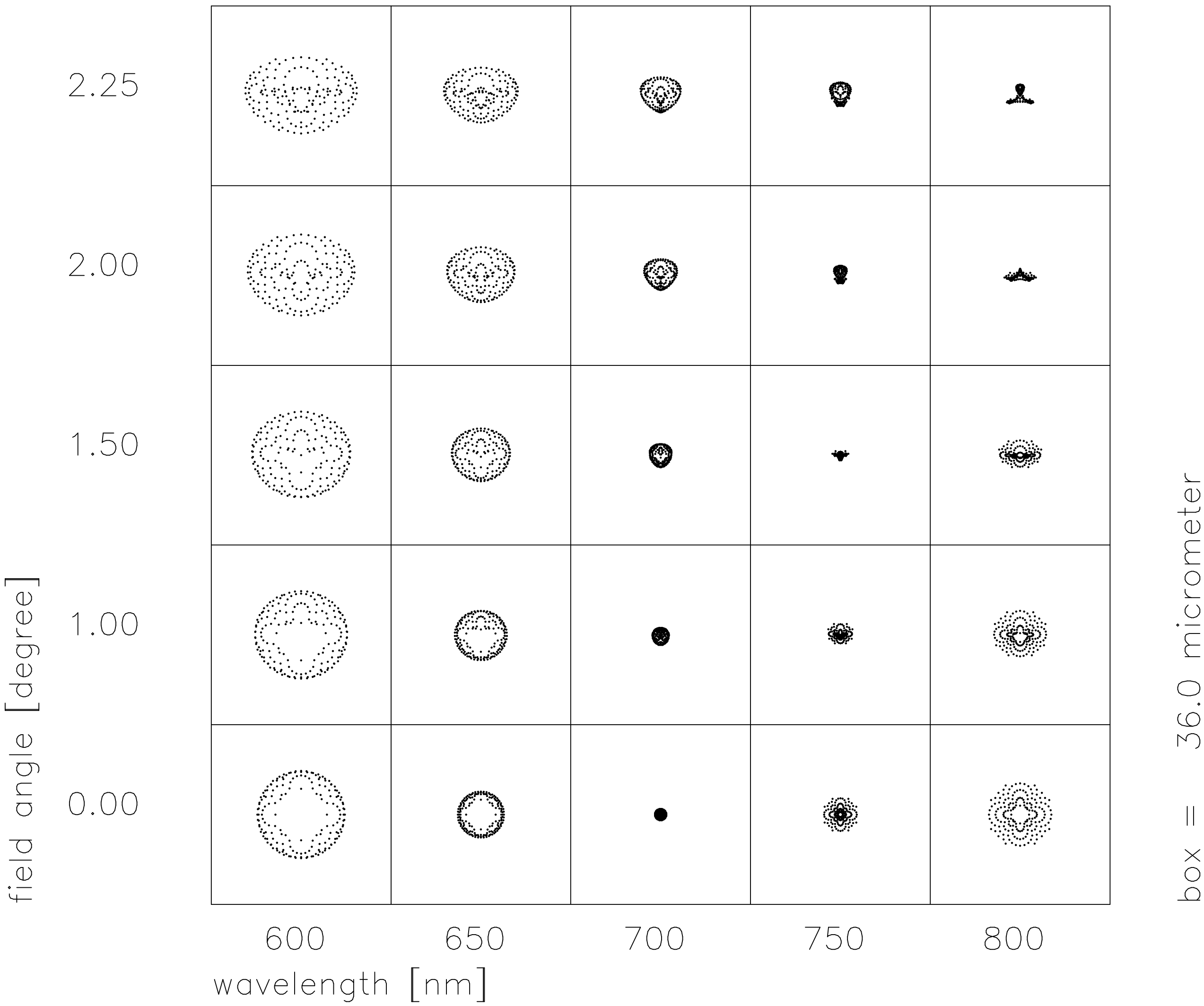

Figure 7. Spot diagrams of FASA2 v4 design.

All but 1 design include only 2 optical elements close to the focal plane: a filter and dewar window, which are given as "+2" on the "number of elements" line in Table 3.

Due to the large central obstruction of the catadioptric designs (about 50% in area) an all-refractive, classical astrograph lens is an option, giving an equivalent throughput with an aperture of about 60 cm. The advantages and disadvantages of the individual design options are:

All-refractive. PRO:

- no central obstruction

CON:

- narrow passband (670–750 nm)
- need folding to fit in existing domes, asymmetric mechanical setup
- availability of optical glass with desired specs is questionable

Table 3. Comparison of initial optical design options for URAT.

	refractive	RS2b	1CaF	RS3	FASA2
number of elements	4 + 2	4 + 2	5 + 2	4 + 2	6 + 2
number of mirror aspheres	0	1	2	2	1
number of lens aspheres	1	1	1	2	1
required glass	special	fus. sil.	CaF	BK7, F2	fus. sil.

RS2b. PRO:

- spherical primary mirror
- only fused silica for all refractive elements

CON:

- 2 full-aperture lenses with 1 aspheric surface
- image symmetry not meeting requirements (residual coma)

1CaF. PRO:

- only 1 full-aperture lens, spherical

CON:

- issues with CaF lens (thermal and refractive gradients)
- limited field-of-view, color correction

RS3. PRO:

- few elements, smallest amount of glass

CON:

- 2 full-aperture corrector plates
- 2 highly aspheric surfaces on corrector plates
- F2 optical glass for corrector plate may be problematic

FASA2. PRO:

- only fused silica for all refractive elements
- only 1 refractive asphere on sub-aperture lens
- spherical secondary mirror
- nearly no geometric optical distortion at all

CON:

- number of surfaces is large, sub-aperture lenses double-pass
- largest central obstruction of presented design options

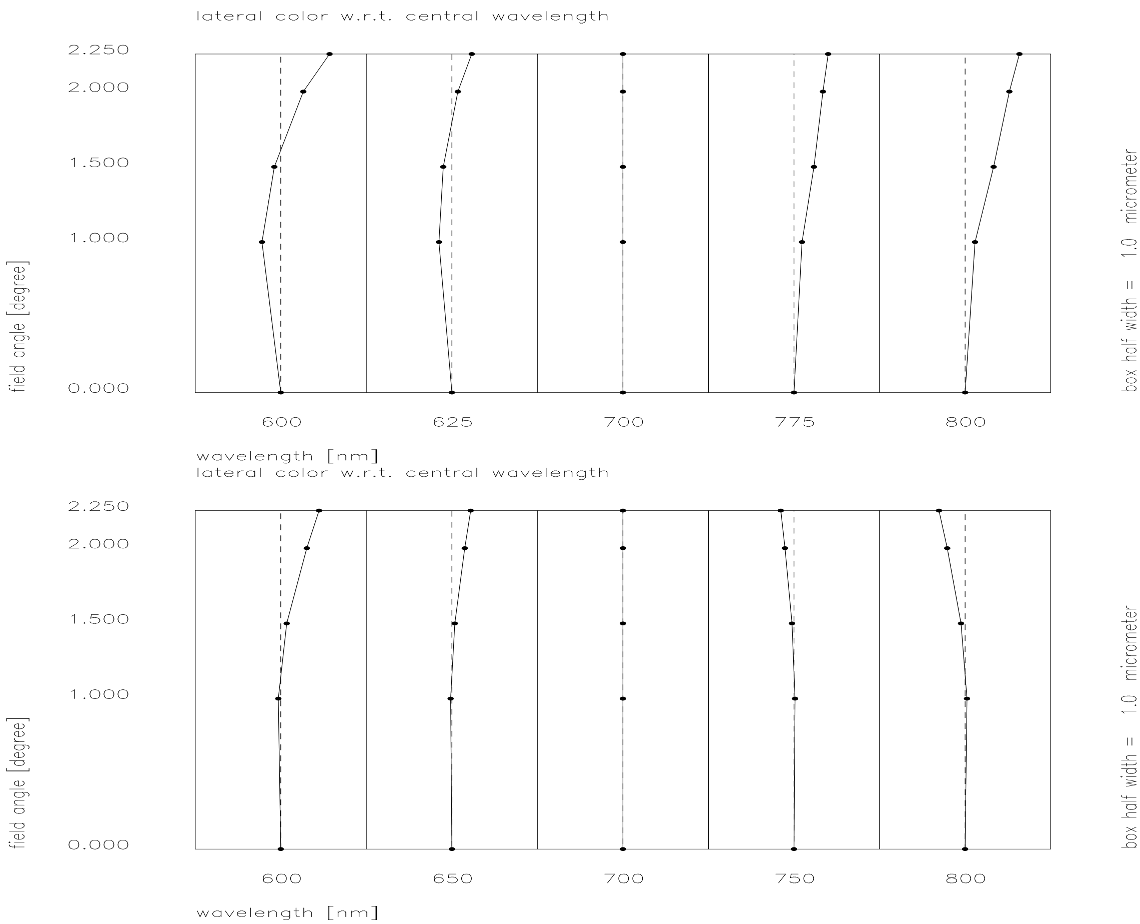

Figure 8. Lateral color diagrams for RS3 (top) and FASA2 (bottom) ideal designs.

4. SELECTION OF DESIGN

The all-refractive option was discarded when the requirement for a photometric survey option arose. The RS2b design has a residual amount of higher order coma which gives rise to stellar image profile asymmetries exceeding the strict requirements set for URAT. The 1CaF design did not meet the later requirements for a larger field of view, has larger color errors than RS3 or FASA2, and the CaF lens is problematic due to the large gradients in thermal expansion and refractive properties combined with the alignment tolerances and stability requirements. The RS3 and FASA2 designs have almost equivalent optical performance. Spot diagrams of the ideal, as designed RS3 and FASA2 systems are given in Figures 6 and 7, respectively.

However the RS3 design has 2 highly aspherical surfaces on the corrector plates and requires BK7 and F2 (or similar) optical glass. By the end of 2005 the FASA2 design[13] was adopted as URAT baseline due to easier manufacturability as compared to the RS3 design.

5. ASTROMETRIC PERFORMANCE

Figure 8 shows the lateral color for the RS3 and FASA2 designs. Both are acceptable for URAT.

For the FASA2 design "as-built" point spread functions (PSFs) were generated with the adopted tolerances and manufacturing errors. Figure 9 shows example contour plots of these PSFs at 2 worst-case locations in the focal plane (left, right), for 650 nm (top), 800 nm (middle) monochromatic, and flat-weighted polychromatic data (bottom). The contour levels are 90%, 70%, 50%, 30%, 10%, and 5%.

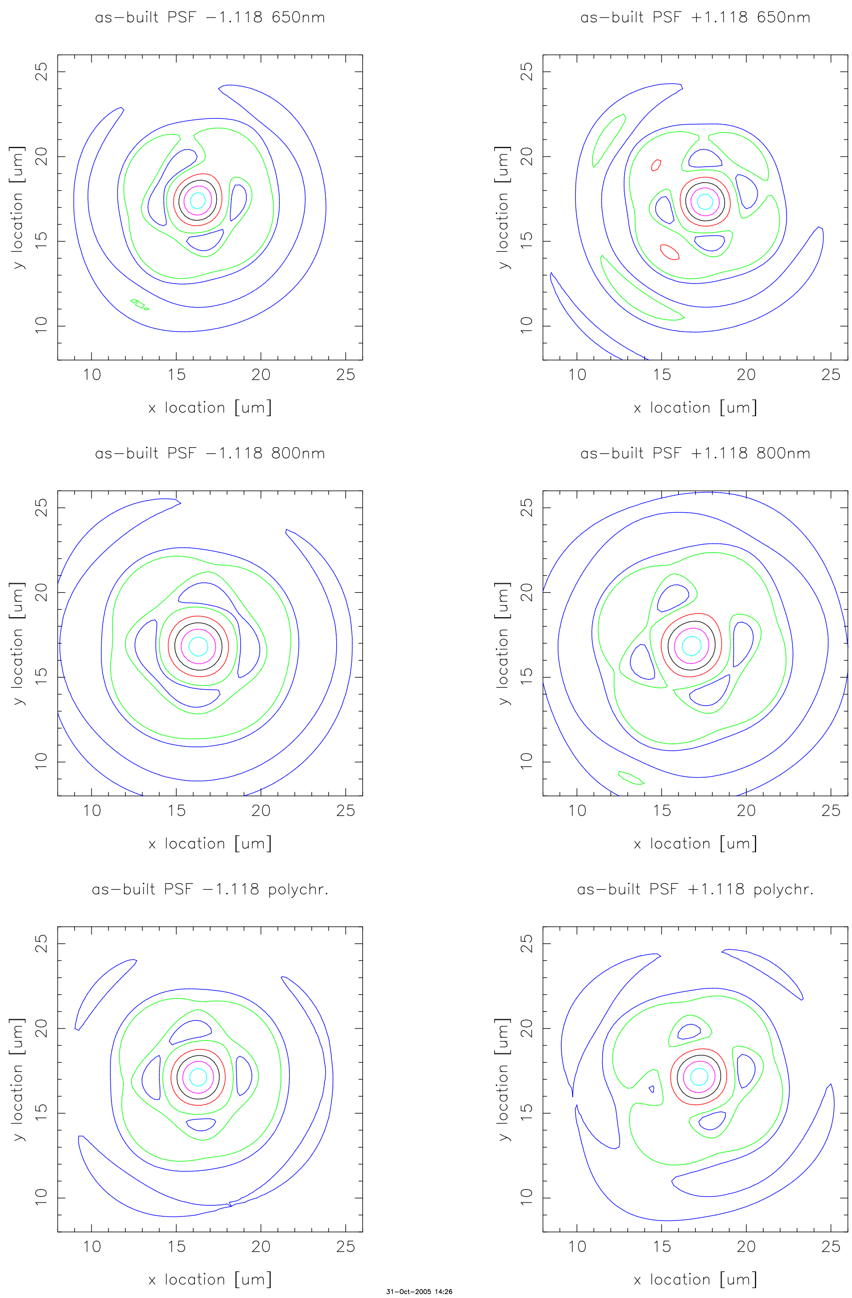

Figure 9. “as-built” PSFs contour plots of FASA2 design.

After folding with a symmetric Gaussian function representing realistic seeing conditions from 0.4 to 1.6 arcsec FWHM the image profiles look even more symmetric. For a quantitative analysis, image centroids were calculated with the simple “center-of-mass” algorithm cutting the profile at various contour levels. For lateral color investigations the maximal position differences (in μm) are summarized in Table 4. The PSF peaks are defined by the 90% flux level and above. On the left hand side the position differences for the extreme, monochromatic colors (650 nm and 800 nm) are listed, separately along the x and y axis (meridional and sagittal, respectively). On the right side the differences between 2 polychromatic PSFs are shown, with weighting of 1,1,2,5 for 650, 700, 750 and 800 nm respectively for a red star and weighting 5,2,1,1 for a blue star.

Table 4. Lateral color from "as-built" FASA2 design PSFs for sample points in the focal plane and extreme monchromatic wavelengths (650−800 nm) as well as polychromatic (blue−red star, see text). Maximal position differences in μm are listed for original PSF and after folding with 0.8 arcsec FWHM seeing, separately for the x and y axis.

field	monochromatic				polychomatic			
	orig. PSF		0.8" seeing		orig. PSF		0.8" seeing	
point	x	y	x	y	x	y	x	y
on axis	0.38	0.54	0.11	0.16				
-1.118	0.03	0.59	0.20	0.30				
+1.118	0.77	0.49	0.13	0.01	0.35	0.23	0.07	0.01
-1.500	0.17	0.64	0.20	0.27				
+1.500	0.91	0.49	0.11	0.01	0.22	0.15	0.01	0.01

Table 5. Position differences (μm) between extreme (90% and 1%) contour levels for the "as-built" FASA2 design PSFs. Data are shown for the original PSF and after folding with 0.4, 0.8, and 1.6 arcsec seeing, separately for the x and y axis.

field		along x-axis				along y-axis			
point	color	orig	0.4	0.8	1.6	orig	0.4	0.8	1.6
on axis	650	0.58	0.44	0.22	0.07	0.95	0.68	0.31	0.05
	800	0.25	0.25	0.17	0.10	0.40	0.40	0.23	0.09
	poly	0.47	0.35	0.19	0.08	0.80	0.53	0.38	0.07
-1.118	650	0.10	0.17	0.17	0.10	0.96	0.78	0.41	0.06
	800	0.13	0.11	0.07	0.10	0.40	0.38	0.22	0.11
	poly	0.05	0.10	0.10	0.10	0.71	0.55	0.28	0.07
+1.118	650	1.29	0.73	0.27	0.09	0.96	0.64	0.29	0.05
	800	0.28	0.30	0.28	0.16	0.48	0.47	0.30	0.11
	poly	0.84	0.54	0.27	0.11	0.78	0.58	0.29	0.07
	polB	1.06	0.61	0.28	0.10	0.88	0.60	0.30	0.06
	polR	0.62	0.41	0.28	0.14	0.64	0.53	0.29	0.09
-1.500	650	0.04	0.24	0.22	0.09	1.05	0.88	0.47	0.06
	850	0.29	0.23	0.12	0.10	0.42	0.38	0.23	0.11
	poly	0.17	0.19	0.14	0.10	0.72	0.58	0.30	0.08
+1.500	650	1.25	0.63	0.23	0.09	0.99	0.67	0.31	0.05
	850	0.10	0.17	0.23	0.17	0.48	0.52	0.32	0.11
	poly	0.73	0.43	0.24	0.12	0.81	0.61	0.31	0.08
	polB	0.67	0.41	0.24	0.12	0.72	0.61	0.32	0.07
	polR	0.48	0.30	0.23	0.16	0.64	0.57	0.32	0.10

Image symmetry has been quantified similarly using "center-of-mass" image positions derived at extreme (90% and 1%) contour levels. A position derived from the peak location of an image profile would correspond to an astrometric observation of a faint star, while for a bright star the entire profile starting at a low level above the background would be used for a position fit. For symmetric images there would be no difference in position. This is even true for astigmatic images with different profile widths along 2 axes. For asymmetric image profiles (coma aberration) however there is such a "magnitude equation", a systematic error in star position as a function of the brightness of the star. The dominant source of coma here comes from alignment errors. Thus alignment tolerances are very tight for astrometric instruments. Image asymmetry is typically not tolerable on a level where the the optical design would still give acceptable performance as judged by the Strehl ratio alone.

Table 5 lists the position differences (μm) between extreme contour levels of the same PSF. These numbers have been obtained from the original "as-built" FASA2 design PSFs as well as after folding with 0.4, 0.8, and 1.6 arcsec seeing. Again, results are presented separately for the x and y coordinate (meridional and sagittal, respectively). For each field point, monochromatic as well as polychromatic PSFs are analyzed, with "poly" meaning a flat-weighted polychromatic PSF while "polyB" and "polyR" are for the aforementioned blue and red stars, respectively.

For 0.4 arcsec seeing, position offsets between peak and low-level contour centroids exceed the requirement, while results for 0.8 arcsec seeing and more are well below the 400 nm position difference requirement. Acceptable astrometric performance with respect to image asymmetry is expected for about 0.7 arcsec seeing, which is sufficient for the envisioned survey work of URAT.

Thermal and mechanical details of URAT are currently under investigation. A slight change of focus (scale) from exposure to exposure is tolerable, however, higher order geometric distortions as well as residual color and magnitude dependent systematic errors need to be constant to high precision (0.1 μm level). More details on the FASA2 design can be found elsewhere in these proceedings.[13]

REFERENCES

1. N. Zacharias et al. "The Second U.S. Naval Observatory CCD Astrograph Catalog (UCAC2)," *AJ* **127**, p. 3043, 2004
2. Chr. de Vegt, "New type of astrometric telescope," in *Star Catalogs: A centennial tribute to A.N. Vyssotsky*, eds. A.G.D. Philip & A.R. Upgren, L. Davis Press, Schenectady, NY, p. 51, 1989
3. N. Zacharais, "Astrometric surveys in support of large telescopes," in *title-proceedings*, T. A. Tyson & S. Wolff eds., *Proc. SPIE* **4836**, pp. 279, 2002
4. D. Pascue et al., "Solar System Astrometry," in *The Future of Solar System Exploration, 2003–2013*, M. V. Sykes ed., *ASP Conf. Series* **272**, pp. 361-374, 2002
5. N. Zacharias, "Astrometric reference stars: from UCAC to URAT," in *3rd Potsdam Thinkshop on robotic telescopes*, *AN* **325**, p. 631, 2004
6. N. Zacharias, "The URAT Project," in *Astrometry in the Age of the Next Generation of Large Telescopes*, P. K. Seidelmann & A. K. B. Monet eds., *ASP Conf. Series* **338**, p. 98, 2005
7. R. Bredthauer, "STA1600," *technical data sheet*, Semiconductor Technology Associates (STA), 2006
8. M.P. Lesser & D.B. Ouellette, "Development of hybridized focal plane technologies," in *High Energy, Optical, and Infrared Detectors for Astronomy II*, SPIE, **6276**, 2006 (in press)
9. J.L. Richter, "Spider diffraction: a comparison of curved and straight legs," *Appl. Opt.* **23**, pp. 1907-1913, 1984
10. J.E. Harvey & C. Ftaclas, "Diffraction effects of telescope secondary mirror spiders on various image-quality criteria," *Appl. Opt.* **34**, pp. 6337-6349, 1995
11. U. Laux & N. Zacharias, "URAT optical design options and astrometric performance," in *Astrometry in the Age of the Next Generation of Large Telescopes*, P. K. Seidelmann & A. K. B. Monet eds., *ASP Conf. Series* **338**, p. 106, 2005
12. Chr. de Vegt, U. Laux, N. Zacharias, "A dedicated 1-meter telescope for high precision astrometric sky mapping of faint stars," in *Small Telescopes in the New Millenium II.*, T. Oswalt ed., Kluwer Acad. Publ. p. 255, 2003
13. A. Rakich, "FASA2 optical design for URAT", SPIE, this volume, 2006